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Computer aided design of an electrostatic FIB system

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Abstract A computer-aided design of focused ion beam (FIB) system consisting of three electrostatic lenses approximated by the spline lens model, has been investigated in the present work In a lens system, there may exist between the electrostatic lenses either a collimated ion beam (a bundle of charged particles travelling parallel to the optical axis) or a beam crossover. The two-interval spline lens model is used in the synthesis procedure to construct einzel and immersion electrostatic lenses with as small aberrations as possible. In the beam crossover system, the axial gap between the electrostatic lenses has been investigated as an important parameter for improving the performance of the lens system. Non-relativistic velocities of charged particles and neglecting the space-charge effect, are the two main assumptions that have been taken into account throughout the work. A two-dimensional diagram of the electrodes has been determined which shows that they can be practically realized.

Keywords FIB system, electrostatic lenses, beam crossover, ion beam and ion optics.

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1. Introduction

Focused ion beam (FIB) system is a combination of electrostatic lenses and deflectors that can provide a beam of charged particles of high current density and small spherical and chromatic aberrations. It is one of the most promising technologies for submicron microfabrication, which has certain features for application to lithography and maskless processes [1,2]. It may also be used for direct writing onto wafers, mask fabrication, implantation (doping), direct ion milling, deposition, and for producing bombardment damage to enhance sputtering and etching.

The bright ion source and the high resolution ion optics column with a wide scanning area are the most important and complimentary elements of the FIB systems [3]. In order to achieve a high current density beam, an electrostatic lens system with low aberrations is required. The einzel lens is typically used since the object-side and image-side beam energies are not affected by variations in its excitation, a desirable property for the objective lens of a focused ion beam system. Tsumagari *et al* [4] investigated the optimization of the relative displacement in an electrostatic two-lens system with an intermediate beam crossover. Many authors introduced various designs of electrostatic FIB system taking into account the beam spot size and the aberrations of the system [2,3,5]. Sometimes it is difficult to determine what is the optical system for the application at hand, becuase there are some controversial demands.

The present work is aimed at putting forward a design of a focusing system with aberrations as small as possible. The effect of the axial gap between the electrostatic focusing elements where the ion beam crossover occurs on the optical properties, has been investigated. The importance of the present investigation lies in the possibility of studying the effect of the exial gap independently of the electrodes geometry with the aid of the two-interval spline lens model.

2. Design of electrostatic lenses

Design of electrostatic lenses may be accomplished by following one of the two main procedures, namely analysis and synthesis [6]. In the present work, synthesis of electrostatic lenses have been considered as a design procedure with the aid of two-interval spline lens model.

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The suggested axial potential distribution $U_k(z)$ at the k-th interval in each lens is represented by the following cubic polynomial [6] :

$$U_k(z) = A_k + B_k(z - z_{k-1}) + C_k(z - z_{k-1})^2 + D_k(z - z_{k-1})^3,$$
$$U_k'(z) = B_k + 2C_k(z - z_{k-1}) + 3D_k(z - z_{k-1})^2, \quad (2.1)$$
$$U_k''(z) = 2C_k + 6D_k(z - z_{k-1}),$$

where $U_k'(z)$ and $U_k''(z)$ are the first and second derivatives respectively. The proposed potential distribution for each of the lenses forming the FIB system have been investigated independently in order to achieve the most favorable optical properties under selected operational conditions such that the suggested requirements of the system are fulfilled.

3. Aberration of system of lenses

In case of axial aberration (*i.e.* aberration due to paraxial approximation), the expression for any particular aberration coefficient of the lens system contains the corresponding coefficients of the individual lenses, and they do not depend on the off-axis aberration coefficients of the individual lenses [6]. The spherical aberration coefficients of the two-lens system referred to the object can be expressed as [6] :

$$C_{s\!o} = C_{so}' + \left[\frac{U(z_o) - U_o}{U(z_m) - U_o}\right]^{3/2} C_{so}''/M'^4$$
$$= C_{so}' + \left[\frac{U(z_o) - U_o}{U(z_i) - U_o}\right]^{3/2} C_{si}''/M^4 \quad (3.1)$$

where, z_m is the coordinate of the intermediate image, M' is the magnification of the first lens in the system, M is the total magnification.

$$M = -f_1''/f_2' = -(n_1 f_2')/(n_2 f_1') = -\sqrt{\frac{U_1}{U_2}} \cdot \frac{f_2''}{f_1'}, \quad (3.2)$$

where f_1' and f_1'' are the object-side and image-side focal lengths of the first lens in the system, and f_2' and f_2'' are the object and image-side focal lengths of the second lens in the system respectively. n_1 and n_2 are the refractive index of the lens. The spherical aberration for the system is thus given by the following equation [6] :

$$C_{sso} = C_{so\infty}' - (f_1'/f_2')^3 . C_{si(M=0)}''/M. \quad (3.3)$$

For a given overall magnification M, the spherical aberration coefficient of the system can be made very close to that of the first lens for infinite magnification, if a very strong first lens compared to the second lens was chosen. It is easy to generalize the above result for a chain of lenses by simply considering combinations of lens pairs as single lenses and using the procedure sequentially. By the same method, similar expressions with some differences exist in determining the chromatic aberration coefficient. The chromatic aberration coefficients of the system referred to the object can be expressed by the following equation [6] :

$$C_{sco} = C_{co}' \left[\frac{U(z_o) - U_o}{U(z_m) - U_o}\right]^{3/2} C_{co}''/M'^2$$
$$= C_{co}' + \left[\frac{U(z_o) - U_o}{U(z_m) - U_o}\right]^{3/2} C_{ci}''/M^2 \quad (3.4)$$

where the coefficients C_{co}' and C_{co}'' are functions of the magnifications M' and M'', respectively. The magnification M'' on the other hand, depends on the separation of the two lenses from each other. Therefore, the chromatic aberration coefficient of the compound lens is a complicated function of the system parameters. For a system the chromatic aberration coefficients are given as follows [6] :

$$C_{sco} = C_{co\infty}' - M(f_1'/f_2')^3 C_{ci(M=0)}''. \quad (3.5)$$

The spherical aberration disc radius in the image plane can be written in the following form [6] :

$$R_{si} = M'' R_{si1} + R_{si2}, \quad (3.6)$$

where $R_{si1} = M' C_{so}' \tan^3(\alpha 1)$ (3.7)

is the spherical aberration disk of the first lens, and

$$R_{si2} = M'' C_{so}' \tan^3(\alpha 2) \quad (3.8)$$

is the spherical aberration disc of the second lens, $\alpha 1$ and $\alpha 2$ are the acceptance half angle of the charged particles for the first and second lenses respectively. The chromatic aberration disc radius is given by [6] :

$$R_{ci} = M'' R_{ci1} + R_{ci2}, \quad (3.9)$$

where $R_{ci1} = M'.C_{co}' \tan(\alpha_1) \Delta U_o / \{2[U(z_o) - U_o]\}$ (3.10)

is the chromatic aberration disc of the first lens, and

$$R_{ci2} = M'.C_{co}' \tan(\alpha_2) \Delta U_o / \{2[U(z_m) - U_o]\} \quad (3.11)$$

is the chromatic aberration disc of the second lens and ΔU_o is the energy spread expressed in electron volts. The above relationships indicate that the radius of spherical (or chromatic) aberration disc of the system is the sum of the radius of the spherical (or chromatic) aberration disc of the first lens magnified by the second lens and the radius of the spherical (or chromatic) aberration disc of the second lens. The radii of the spherical and chromatic aberration discs determine the radius of the total aberration disc [6] :

$$R_i = \left(R_{si}^2 + R_{ci}^2\right)^{1/2} \quad (3.12)$$

4. Results and discussion

In the present work, two einzel lenses and a three-electrode immersion lens have been proposed to form the focusing system for the beam trajectory shown in Figure 1. The

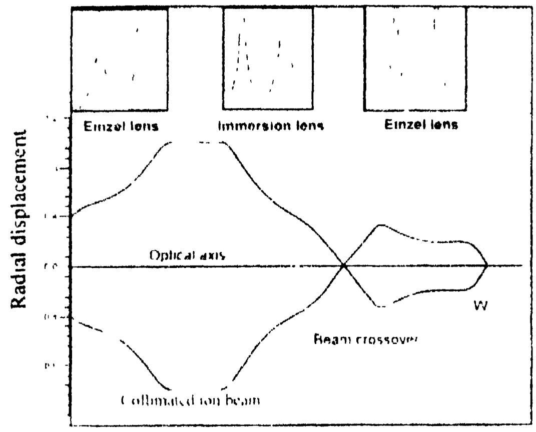

Figure 1. Ion beam trajectory and lenses profiles for the electrostatic three-lens system with an intermediate beam crossover obtained with the aid of two-interval spline lens model.

geometrical axial length of the three lenses is the same and equal to L. The illustrated profile of the three lenses was determined from the equipotential surfaces of radial height R given by Szilagyi [7] :

$$R = \left[4\left(U_k(z) - V\right)/U''(z)\right], \qquad (4.1)$$

where V is the electrode potential for an arbitrary point with coordinates r and z situated in the k-th region. The first einzel lens is for operation under infinite magnification condition. The immersion lens is for operation under zero magnification condition. The collimated ion beam appears between the first and second lens of the system. The second einzel lens is for operation under finite magnification condition. The optical properties of this lens system are listed in Table 1. It is seen that this system demagnifies the image. Demagnification of the beam size in the image plane is one of the requirements of FIB which should be associated with low aberration. The relative aberrations given in Table 1 are considerably low and optically accepted.

Figure 2 shows the ion beam trajectories in the last einzel lens of the system at different values of the axial gap separating the immersion lens from the last einzel lens at which the beam crossover occurs. The beam of charged particles enters the lens with the same acceptance angle at each time and with radial displacement depending on the axial gap itself. However, all the beams would be focused at the same radial displacement inside the lens in the region of the central eletrode.

Figure 3 shows the effect of the relative axial gap G/L on the relative quantities of the image-side focal length

Table 1. The optical properties for three-lens system

	Lens no. 1	Lens no 2	Lens no. 3	System
$U(L/2)/U(z_o)$	2.75	3.25	9 0	
$U(z_i)/U(z_o)$	1.0	1 25	1.0	
Magnification	Infinite	Zero	-0.99	–0.6
W/L	Infinite	0.184	0 34	0.34
F_i/L	Infinite	1.12	0 56	0 56
F_o/L	0.98		0 56	0.98
C_c/f_i		0.68	0.79	
C_{co}/f_o	0 637			4 62
C_s/f_i		9.7	4 44	
C_{so}/f_o	7 18			74.9
R_{si}(μm)		4 07	0 92	1.6
R_{so}(μm)	2.65			
R_{ci}(μm)		15.23	8 82	2.85
R_{co}(μm)	19 68			
R_{ti}(μm)		15 8	8 86	3.27
R_{to}(μm)	19.85			

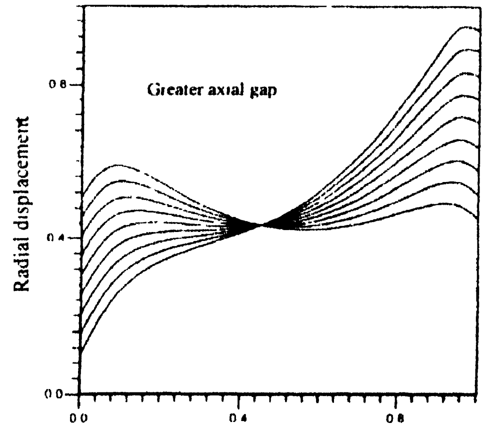

Figure 2. Ion beam trajectories for the third-lens of the electrostatic lens system for different values of the axial gap between the focusing elements.

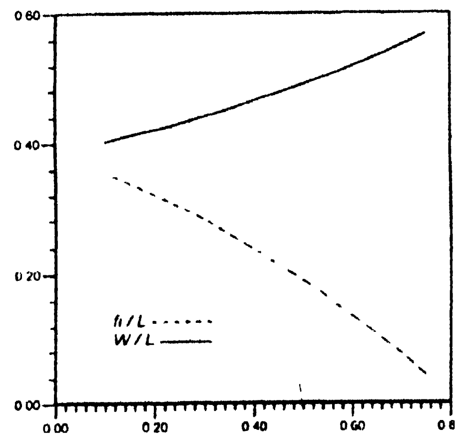

Figure 3. The relative image-side focal length and relative working distance for the third-lens system with an intermediate beam crossover as a function of the axial gap between focusing elements.

f_i/L and the relative working distance W/L. As G/L increases the f_i/L increases while the W/L decreases. This is leading basically from the effect of the spherical aberration itself. The values f_i/L and W/L have no importance without knowing the corresponding values of the relative aberrations.

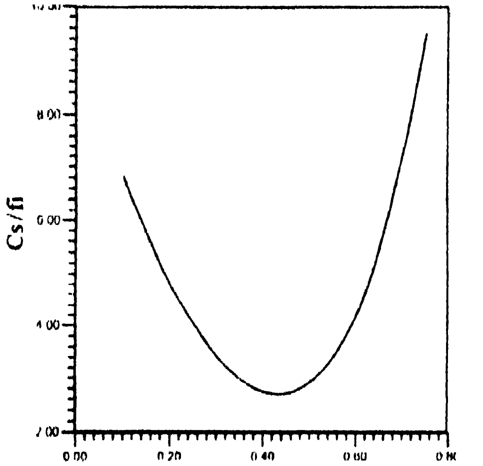

Figure 4. The relative image-side spherical aberration coefficient for the third-lens system with an intermediate beam crossover as a function of the axial gap between focusing elements

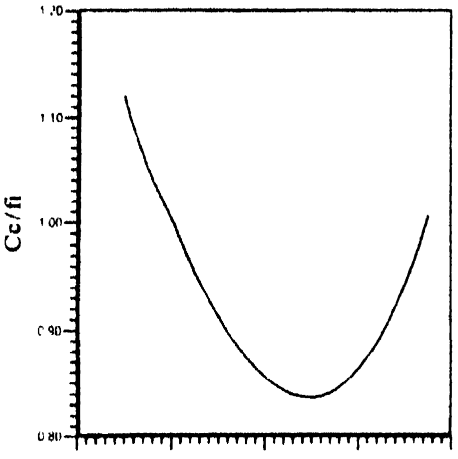

Figure 5. The relative image-side chromatic aberration coefficient for the third-lens system with an intermediate beam crosover as a function of the axial gap between focusing elements.

Figures 4 and 5 show the relative spherical aberration C_s/f_i and chromatic aberration C_c/f_i as a function of the G/L. The two figures show that both C_s/f_i and C_c/f_i have minimum values when G/L equals 5.0 and 4.2 respectively. Thus one has to separate the lenses from each other at the appropriate distance in order to achieve the mininum relative aberrations.

5. Conclusions

It appears from the present work that in addition to the importance of using electrostiatic lenses with low aberrations to construct as focusing system operating with highly desirable optical properties, there are still other parameters have to be taken into account. The axial gap width G in the crossover region is one of the most important parameters that would improve the performance of the lens system. Although the suggested system design has not yet been assessed in practice but it is clear from the computations that it could bring about instrumental developments.

References

[1] K Kurihara *Jpn. J. Appl Phys* **24** 225 (1985)

[2] K Kurihara *J Vac Sci Technol* **B3** 41 (1985)

[3] H Ohiwa *Ultramicroscopy* **15** 221 (1984)

[4] T Tsumagari, Y Kimata, H Ohiwa and T Noda *Jpn J Appl Phys* **27** L1567 (1988)

[5] M Szilagyi *J. Vac. Sci. Technol.* **B9** 2617 (1991)

[6] M Szilagyi *Electron and Ion Optics* (New York : Plenum) (1988)

[7] M Szilagyi *Appl. Phys. Lett* **44** 7 (1984)